Multiphysics Multi-Material Topology Optimization of a Thermal Actuator with COMSOL Multiphysics

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Introduction

Design of a thermally driven actuator used in Micro Electro Mechanical Systems (MEMS) with two different metal materials is discussed. To achieve best performance of the thermally driven actuator in this work, it is desired to use a metal material with both high coefficient of thermal expansion and Young's modulus. However, most of the material with high Young's modulus has relatively small coefficient of thermal expansion, or vice versa. Therefore, it is hard to find the ideal material for the design.

Here we consider two materials, one has high coefficient of thermal expansion but small Young's modulus, the other has high Young's modulus but small coefficient of thermal expansion. By optimizing the distribution of two materials at the same time, it is possible to obtain superior performance by assigning the materials to the right places to utilize each materials' strong point.

To achieve the multiphysics, multi-material optimization, density method with consideration of handling different materials was used for topology optimization of the device. Therefore, distribution of two materials in the design space was considered and density of the materials were used as design variables for the optimization problem. Effective material properties such as Young's modulus and thermal conductivity were determined using interpolation scheme which based on power-law method. A Helmholtz equation based regularization was used as a filter for the design variables. Projection method was also investigated for reducing the grayscale in the optimization results.

Problem Definition

A design of thermal actuator was considered in this paper. Geometry of the design domain is a simple 10[mm^2] square. As shown in Fig.1, only upper half of the square was modeled here, and symmetry condition was adopted at the lower boundary.

In this work, we are going to solve heat transfer problem to determine the temperature distribution across the simulation domain, and use the temperature information to solve a thermal expansion problem to get the deformation behavior of the optimized structure.

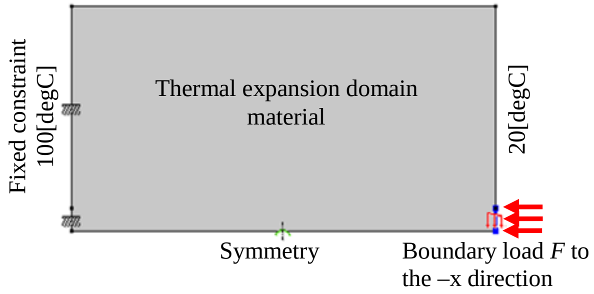

Figure 1. Geometry and boundary conditions of the design problem

As shown in Fig. 1, boundary conditions used for heat transfer problem are set the left boundary to 100[degC] and left boundary to 20[degC]. The upper and lower boundaries were set to thermal insulation. Thermal insulation is equivalent to symmetry for heat transfer problem on the lower boundary.

Boundary condition used for structural mechanics problem is set the left boundary to fix boundary; corner of the right boundary is subject to *F*=10[N] load to the right; the upper boundary is set to free and the lower boundary is set as symmetry.

Two materials was used for the optimization (three if consider void as a material). The objective of the optimization is find the best distribution pattern for limited materials to maximize the displacement of the corner of the right boundary when the temperature difference is applied on the object. Total material can be used need to be =<40% in each volume fraction.

$$\max \frac{\int u(\rho 0,\ \rho 1)dl}{L} \qquad (1)$$

$$0.001<\rho 0<0.4$$

where u is the displacement in x direction near center of the right boundary; L is the length of the center part of the right boundary, $(\rho 0, \rho 1) \in [0,1]$, $\rho 0$ indicates the presence of material or void in the domain ($\rho 0 =$ 0 for void and 1 for mixed material), $\rho 1$ indicates the presence of material 1 or material 2 in the non-void part of the domain ($\rho 1 = 1$ for material 1 and 0 for material 2).

Material Interpolation Scheme

Since the focus of this work is to discuss the topology optimization of objects with multi-materials, the traditional Power-law material interpolation scheme that consider the distribution of only one material (two material if consider “void” as one material) cannot be directly applied. In this paper, a Power-law combined with Linear Material Interpolation scheme was used.

Since Finite Element Method (FEM) was used to solve governing equations for the thermal actuator, effective material properties for the mixed material need to be defined on simulation domain. For the structural mechanics and heat transfer problem, following material properties are needed for solving the equations: Young’s modulus E, Poisson’s ration nu, density rho, coefficient of thermal expansion alpha, thermal conductivity k and heat capacity Cp.

The following Power-law combined with Linear Material Interpolation scheme was used. The similar scheme also known as Solid Isotropic Material Penalization (SIMP) method:

$$E = \rho 0^{p} \cdot (\rho 1 \cdot E1 + (1 - \rho 1) \cdot E2) \qquad (2)$$

$$nu = \rho 1 \cdot nu1 + (1 - \rho 1) \cdot nu2 \qquad (3)$$

where p is the power of the SIMP method. Other material properties, rho, alpha, k and Cp were defined with equations similar to Eq (1).

Material properties of material 1 and material 2 are shown in Table 1 and Table 2.

Table 1: Material properties of material 1

Young’s modulus (GPa)	200
Poisson’s ratio	0.31
Density (kg/m^3)	7850
Coefficient of thermal expansion (1/K)	15e-6
Heat capacity at constant pressure (J/(kg*K))	500
Thermal conductivity (W/(m*K))	50

Table 2: Material properties of material 2

Young’s modulus (GPa)	100
Poisson’s ratio	0.31
Density (kg/m^3)	2100
Coefficient of thermal expansion (1/K)	30e-6
Heat capacity at constant pressure (J/(kg*K))	1000
Thermal conductivity (W/(m*K))	200

Results and Discussion

In this work, Solid Mechanics interface, Heat Transfer in Solids interface and Density Model in the Optimization Module of COMSOL Multiphysics V5.4 are used to set up the multiphysics, multi-material topology optimization model.

MMA method was used to solve the optimization problem. Iteration of the optimization is 200. 3186 triangle mesh was used to discretize the domain. 2.82GB physical memory was used to solve the problem. The solution time is about 12 minutes on a PC with Intel(R) Core(TM) i7-5500U CPU.

The material distribution for material 1 and material 2 is shown in Fig.2. It found that material 2 has been used more than material one is this structure. The reason is considered that thermal expansion of material 2 is twice higher than material 1 for current material choice, and this property is favored in a thermal expansion design problem, also Young’s modulus of material 1 is higher than material 2.

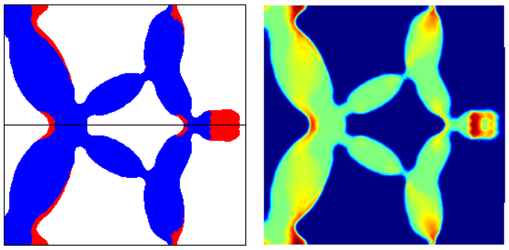

Figure 2. Left: Optimized material distribution, red is for material 1 and blue is for material 2; Right: Distribution of effective Young’s modulus.

Fig.3 shows the distribution of two mixed material in total, distribution of material 2 within the mixed material respectively. Distribution of mixed material has clear boundaries with the void (blue region). This is because Helmholtz filter and projection method were adopted in the model [1]. On the other hand, gray area around material 2 boundaries within the mixed material was not processed. This is considered current 3D print technology can take care of mixed material formulation.

Fig.4 shows von Mises stress and thermal strain distribution. It can be found that thermal strain distribution is similar to material 2 distribution shown in Fig.3, which shows that material 2 with bigger thermal expansion coefficient contributes higher for the thermal deformation.

Fig.5 shows temperature and total heat flux distribution. The temperature is gradually changing from 100[degC] to 20[degC] from left to right boundary as set in the model. Although it is hard to get many detailed information from the temperature distribution since this problem is design with stationary formulation, it can be observed from the heat flux image that it follows the path that coincides with the mixed material distribution.

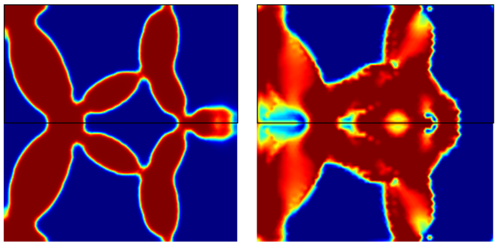

Figure 3. Left: Distribution of $\rho 0$; Right: Distribution of $\rho 1$.

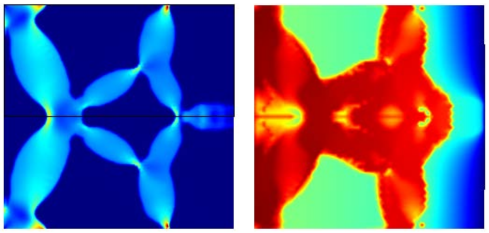

Figure 4. Left: von Mises stress; Right: Thermal strain tensor, 11 component

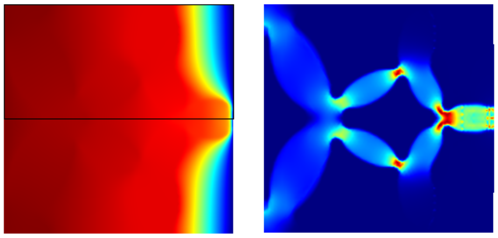

Figure 5. Left: Temperature distribution; Right: Total heat flux magnitude

Conclusions

Topology optimization for multi-physics, multi-material problem was discussed in this paper. The optimal configuration of a two material thermal actuator was designed. The material distribution, the stress and strain, temperature and heat flux path were visualized. The results can be used to provide non-intuitive design idea for innovative micro devices.

References

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2. Kristian Ejlebjærg Jensen: https://www.comsol.jp/blogs/performing-topology-optimization-with-the-density-method/